Estimating capacity of hybrid bus rapid transit corridor

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The main objective of this study is to estimate the capacity of hybrid bus rapid transit (BRT) corridor. By the term hybrid BRT corridor in context to this study, we mean a corridor in which buses have to operate in an exclusive environment as well as in a mixed traffic environment. Capacity is an important parameter to estimate corridor and system performance. Therefore to evaluate the same, Ahmedabad BRT system was chosen in the present study. On the basis of boarding alighting data, the busiest route comprising both segregated (exclusive environment) and unsegregated (mixed traffic environment) stretch was selected. For estimating the capacity, an empirical method was adopted. Bus lane capacity for segregated stretch and unsegregated stretch was estimated as 243 buses/h and 101 buses/h respectively. The overall capacity value of hybrid BRT corridor was minimum of the two, i.e. 101 buses/h. After estimating the capacity so obtained, the effect of mixed traffic environment on overall corridor capacity was observed.

Further, an attempt was made to estimate capacity using conventional Greenshield model on a mid-block section. Following this, the results of two approaches namely, empirical model capacity and capacity using Greenshield model were compared. The capacity obtained at mid-block section of the segregated stretch was overestimated by 19.34% or 290 buses/h compared to that obtained using empirical method (243 buses/h).

Keywords: Hybrid bus rapid transit, Greenshield model, population, traffic.

BUS rapid transit system (BRTS) is a high-capacity articulated bus service with buses operating in lanes reserved for their exclusive use. It is an innovative form of transit system, especially for developing countries like India, Brazil and China, the reason being its minimal capital costs, larger capacity, increased ridership, and efficient door-to-door services meeting the daily commute needs of citizens. Encouraging public transportation like BRT in Indian cities helps in sustainable development[1], i.e. one that satisfies the current mobility needs without compromising the ability of future generations to meet these needs[2]. BRT offers enhanced frequencies, increased system reliability and a reduction in travel time and delays.

The population of India, 1.21 billion[3], is the second largest in the world. Around 30% live in urban areas. Due to this there are many transportation problems like urban sprawl, traffic congestion, air pollution, etc. Hence, there is an immediate need for improving the transportation systems around urban cities[4]. These problems can be resolved by the implementation of alternatives like BRTS which is a rapid mode of transportation that can combine the quality of rail transit and the flexibility of buses[5]. Mass rapid transit (MRT) and light rail transit (LRT) require heavy initial investments and maintenance costs[6]. BRTS incorporates low-cost technologies that result in more passengers and less congestion[7]. BRT construction is faster and easier when compared to other transitway construction.

BRTS in India is currently operational in various cities of India. Therefore, it is prudent to estimate BRT bus lane capacity which further helps understand the current condition of the system and how it can accomplish the future transit demand.

Transit facility can be classified into four main types of operating environments on the basis of protection from other vehicles. These are grade-separated (no interactions with other vehicles), exclusive (interactions with other vehicles only at intersection), semi-exclusive (other vehicles are allowed to use facility under certain circumstances e.g. exclusive bus lanes allowing right turning traffic at intersections) and mixed traffic (buses operate in the same lanes as other traffic) environment[8]. As BRTS is evolving in many countries including India, there are places where BRT buses also have to operate in mixed traffic environment apart from other traffic environments. Apart from this, capacity is also an important attribute to estimate corridor performance.

This study estimated the capacity of a hybrid BRT corridor, i.e. a transit system in which buses operate in an exclusive and mixed traffic environments. In literature, most of the methodology focusses on capacity estimation of conventional transit systems. Studies estimating capacity, exclusively for BRTS are scarce[9]. Also, there is no study that estimates capacity of hybrid BRTS, although we do find few studies estimating capacity of transit systems in mixed traffic environment. Therefore, there is a need to estimate the capacity of hybrid BRT corridor.

As part of our objective, Ahmedabad BRTS was chosen. For capacity estimation of hybrid network, an empirical method was adopted. An attempt was made to compare the stop capacity value obtained from the empirical model with the capacity value obtained using conventional model, i.e. Greenshield model on a mid-block section. On the basis of boarding alighting data, hybrid corridor comprising of busiest stops was selected. Data was collected and parameters such as mean dwell time, failure rate, space mean speed, volume, etc. were

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extracted. Capacity was estimated using these input parameters in the methodologies adopted. Finally, the results were compared and conclusions drawn.

Bus lane capacity is determined by estimating the capacity of the critical bus stop[10,11]. Critical bus stop is one with least capacity among all bus stops in a particular bus corridor[8]. It is generally the busiest stop[12]. The critical stop acts as a bottleneck which hinders the flow of buses along the route[8]. The procedure for estimating bus lane capacity involves calculation of loading area (bus berth) capacity and bus stop capacity (B_s)[8,13,14]. Parameters involving estimation of loading area capacity are average dwell time, dwell time variability, effective green time, clearance time between buses, failure rate, etc.[8]. Bus stop capacity is determined from the number of loading areas on a particular bus stop using the concept of effective loading areas[8].

Initially, Highway Capacity Manual (HCM)[15,16] provided an equation for estimation of bus lane capacity. Capacity estimation uses multiplicative adjustment factor (which accounts for variations in bus arrival headway) apart from other basic factors like dwell time, etc. These equations were revised in the Transit Cooperative Research Programme (TCRP) report 26 to incorporate probability of queue formation at bus stops[13].

The HCM[17] provides a model to estimate capacity of single-berth stop. The capacity here is inversely proportional to the sum of average dwell time and another term comprising of both the variation in dwell time and the failure rate as presented in eq. (1)

$$B_{bb} = \left(\frac{3600(g/c)}{t_c + t_d(g/c) + t_{om}} \right) = \left(\frac{3600(g/c)}{t_c + t_d(g/c) + Z\sigma} \right), \quad (1)$$

where B_{bb} is the maximum number of buses per berth per hour (buses/h); g/c the green time ratio (the ratio of effective green time to total traffic signal cycle length, equals 1.0 for unsignallized streets and bus facilities); t_c the clearance time (sec) = $t_{su} + t_{re}$; t_{su} the minimum time for a bus to start up, travel its own length, and the next bus to pull into the loading area (s) (default of 10 s); t_{re} the re-entry delay (s); t_d the average (mean) dwell time (s); t_{om} the operating margin (s); Z the standard normal variable corresponding to a desired failure rate; σ is the standard deviation.

The capacity of the stop increases with increase in failure rate which is defined as the percentage of buses arriving at the bus-stop and finding it already occupied. For multiple berths, HCM uses the concept of number of 'effective' berths taking into account the blocking effect of the front loading area on the rear loading area. The recent HCM[18] uses procedure provided in TCQSM to estimate bus lane capacity. TCQSM[8] provides systematic procedure for estimation of the capacity of bus transit considering all factors like dwell time, coefficient of variation (C_v), failure rate, re-entry delay, etc.

Wright and Hook[19] considered parameters like degree of saturation, dwell time, number of stopping stations, frequency (vehicle/h), and vehicle capacity (number of passengers/vehicle) to estimate capacity of BRT system as presented in eq. (2)

$$C_o = \frac{N_{sp} * X * 3600}{\left[\frac{T_d * (1 - D_{ir})}{C_b} + (\mathrm{Ren} * T_l) \right]}, \quad (2)$$

where C_o is the corridor capacity (in terms of passengers per peak hour per direction or pphd); N_{sp} the number of stopping bays; X the saturation level; 3600 the number of seconds in an hour; T_d the dwell time; D_{ir} the percentage of vehicles that are limited-stop or express vehicles; C_b the capacity of the vehicle; Ren the renovation rate; T_l is the average boarding and alighting per passenger.

Gu *et al.*[20] estimated capacity for curbside stops by developing models. These stops were isolated from the effects of traffic signals. This study estimated the capacity for Poisson bus arrivals (capacity independent of the variation in bus service time), uniform bus arrivals (assuming Erlang-k distribution for bus service time variation) and general bus arrivals (assuming Erlang-j distribution for bus headways variation).

Equation (3) gives normalized capacity of single-berth stops for general bus arrival. Models also predicted disproportional gain in capacity with increase in number of berths

$$\frac{\lambda}{\mu} = \mathrm{FR}^{\left(\frac{0.43C_h + 0.59C_s - 0.29C_h * C_s}{1 - 0.57C_h + 0.59C_s - 0.29C_h * C_s} \right)}, \quad (3)$$

where λ/μ is the normalized capacity; λ the capacity of the stop at a specified failure rate (FR); μ the maximum service rate (output flow of the stop when FR = 1); C_h the coefficient of variance of bus arrival headways; C_s the coefficient of variance in bus service time. Sharma *et al.*[21] implemented empirical model mentioned in TCQSM to estimate the capacity of Bhopal BRTS. The bus lane capacity value estimated was 41 buses/h.

There were also studies that estimated capacity using micro-simulation techniques[22–27]. Chen *et al.*[28] used microsimulation models to estimate bus lane capacity and it was applied to bus lane systems where buses were forced to interact with mixed traffic. Reilly and Aros-Vera[12] implemented ARENA microsimulation software to estimate bus lane capacity of Bogota BRTS by varying failure rate from 5% to 25%. Godavarthi *et al.*[4] used VISSIM microsimulation software to evaluate the performance of Delhi and Ahmedabad BRTS. The study showed that at 0.688 V–C ratio both bus lane user and mixed vehicle lane users operate at reasonable speeds. The aforementioned studies focused on either mixed traffic

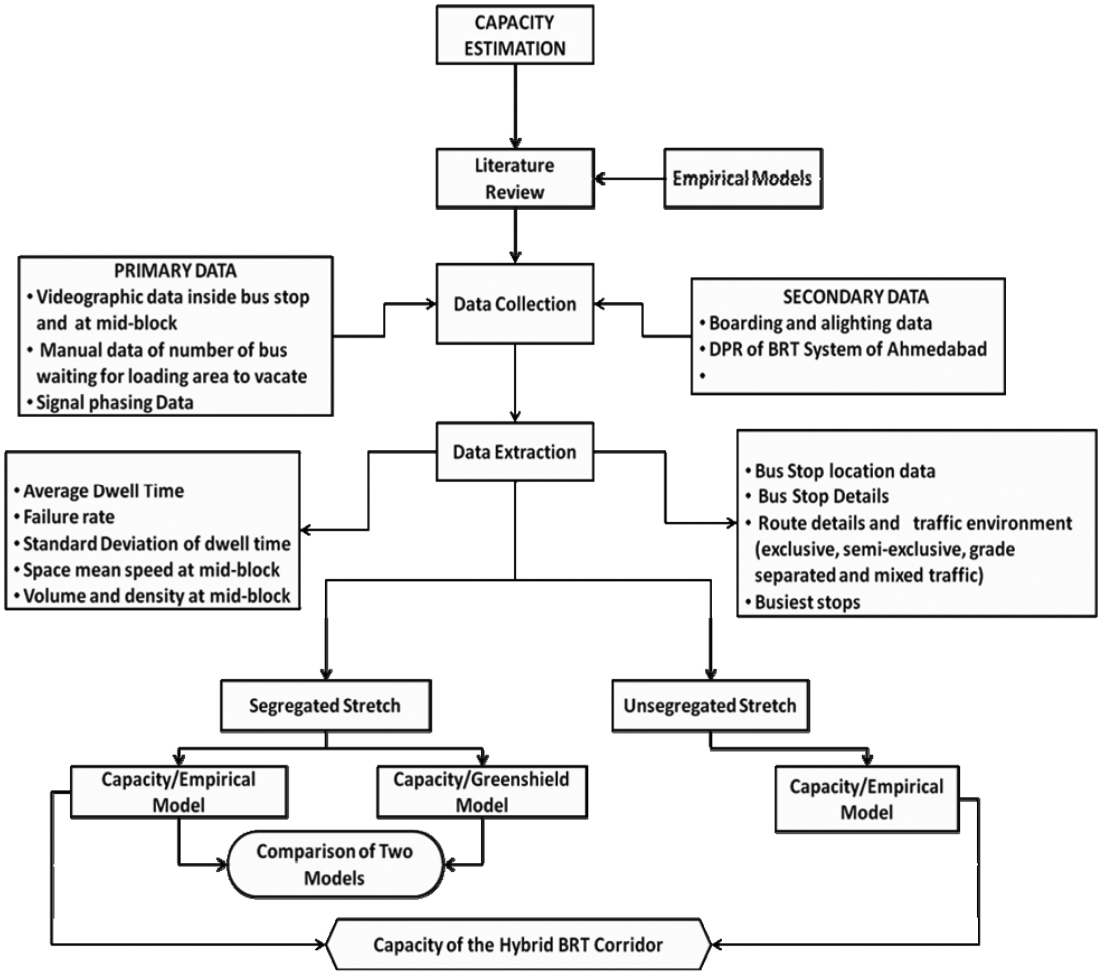

Figure 1. Methodology flow-chart.

lane or exclusive lane capacity but no study was reported for estimating the hybrid capacity of corridor having both exclusive and mixed traffic BRT sections.

After going through literature and the basis of earlier studies, the methodology adopted for capacity estimation of hybrid BRT corridor is discussed here. The required primary and secondary data was collected. The collected data was processed to obtain input parameters. These parameters were used to obtain capacity of hybrid BRT corridor. For capacity estimation, empirical method was adopted. The basic equation for capacity estimation is

$$B = \mathrm{Ne} * \left(\frac{3600(g/c)}{t_c + t_d(g/c) + t_{om}} \right) = \mathrm{Ne} * \left(\frac{3600(g/c)}{t_c + t_d(g/c) + Z\sigma} \right), \quad (4)$$

where B is the bus-stop capacity (buses/h) and Ne is the number of effective loading area.

This study also implemented Greenshield model for capacity estimation of BRTS. It was applied for segregated stretch of hybrid BRT corridor (i.e. the stretch in which buses move in exclusive environment). After this, a comparative evaluation was carried out between empirical model and Greenshield model. On the basis of this evaluation, the applicability of Greenshield model to BRTS was checked. Figure 1 shows complete methodology in the form of stage-wise flowchart.

To complete the objectives, the Ahmedabad BRTS was selected for the study, which is a hybrid BRTS consisting of both segregated stretch (exclusive environment) of BRTS as well as unsegregated stretch (mixed traffic environment) of BRTS.

Ahmedabad BRTS is a huge network consisting of a large number of bus stops. So the first aim was to choose an appropriate set of bus stops which could yield the capacity of the system. For this purpose, boarding and alighting data was taken for every bus stop from Ahmedabad Janmarg Limited on a normal working day in June 2015. A majority of passengers bought tickets at the bus stop counter but there were also others who travelled by smart card.

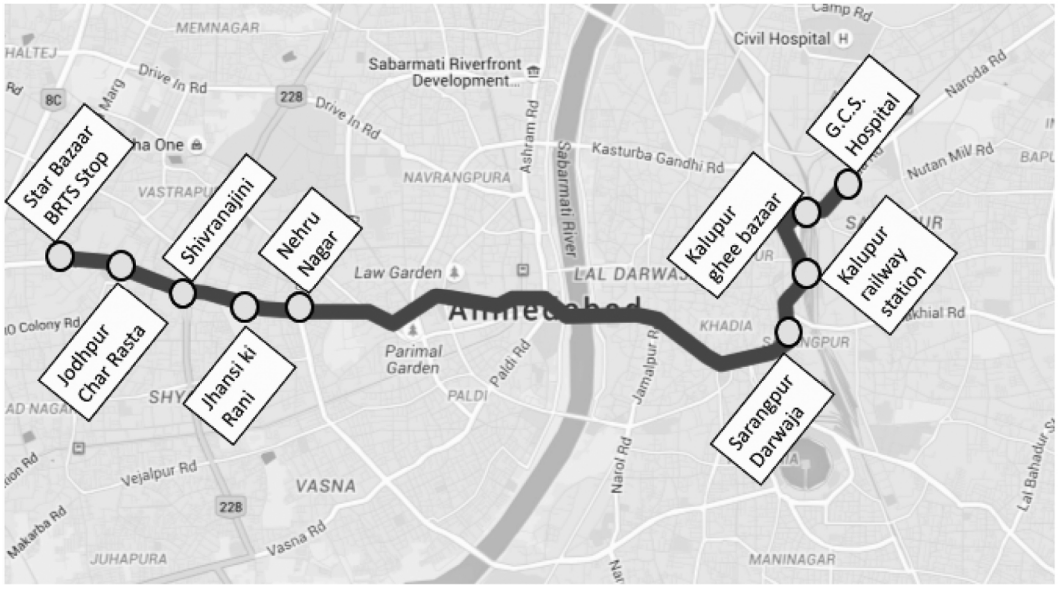

Figure 2. BRTS route selected for capacity analysis.

From the boarding alighting data, the busiest stops were found. On segregated stretch, the busiest stops were Shivranjini, Jhansi ki Rani and Nehru Nagar. Further, Kalupur railway station bus stop, Kalupur Ghee Bazaar stop and Sarangpur Darwaza stop were busiest on unsegregated stretch.

On the basis of the aforementioned findings, a BRTS corridor was selected which consisted of all these bus stops, so that we could cover segregated as well as unsegregated stretches and the bus stops could yield capacity of the hybrid BRT corridor. The selected BRTS route is depicted in Figure 2.

Bus stops chosen for data collection were: (a) For segregated stretch – Nehru Nagar, Jhansi ki Rani, Shivranjini, Jodhpur Char Rasta and Star Bazaar. (b) For unsegregated stretch – Sarangpur Darwaza, Kalupur Railway Station, Kalupur Ghee Bazaar and G.C.S. Hospital.

The segregated stretch was 5 km long and the unsegregated stretch was 4.5 km.

Dwell time data was obtained using field survey as it is the most accurate method to measure bus dwell times[8]. Dwell time data was collected on selected bus stops by videography. There were two loading areas (berths) at each bus stop.

Data was collected for four hours on each of the chosen bus stops during peak period. The procedure mentioned in Transit Capacity and Quality Service Manual[8] was adopted for field data collection of dwell time. Dwell time data was extracted for all BRTS stops of the selected corridor.

Further, the distribution fit of the dwell time data was done using EasyFit software. It was observed that dwell time data of all BRTS stops fits into normal distribution curve considering 95% confidence limit.

The statistical result of dwell time data for various BRTS stops along segregated and unsegregated stretch is illustrated in Tables 1 and 2.

In Table 2 there is no data of loading area 2 for a few of the stops because none of the buses stopped at the second loading area of these bus stops.

Failure rate is defined as the percentage of buses arriving at the BRTS stop and finding the loading area already occupied. The more the failure rate the more is the capacity[8]. Bus loading area capacity is maximized when a bus is available to move into a loading area as soon as the previous bus vacates it. However, this condition is undesirable for several reasons: (a) bus travel speeds are reduced, due to the time spent waiting for a loading area to become available; (b) additional delays affect bus schedule reliability; and (c) traffic is blocked by buses in the street while waiting to enter the bus stop[8]. The more often the bus stop failure occurs, the higher the bus throughput over the course of the hour, but more severe the corridor operation. Hence it is necessary that failure rate should be within limits[8]. Failure rate obtained at various stops is illustrated in Table 3.

Traffic signal data affects the capacity only if BRT stops are located at the traffic signals, i.e. when the bus is not able to enter or leave the bus stop immediately after serving passengers[8]. Since none of the bus stops was away from the influence of traffic signals, the traffic signal data was not required and g/c ratio was taken as 1 for every bus stop.

Mathematically, loading area capacity is expressed as in eq. (4) when the clearance time (t_c) has two components: (a) a fixed minimum amount of time for a bus to start up and travel its own length, and for the next bus to pull in (taken equal to 10 sec) and, for off-line stops, (b) a

Table 1. Statistics results of dwell time data at various stops along segregated stretch

Directions	Naroda to Iskon				Iskon to Naroda			
	Loading area 1		Loading area 2		Loading area 1		Loading area 2	
Bus stop name	Average dwell time(s)	Std. Dev.	Average dwell time(s)	Std. Dev.	Average dwell time(s)	Std. Dev.	Average dwell time(s)	Std. Dev.
Star Bazaar	9.54	5.42	6.04	1.87	9.47	3.49	6.55	2.87
Jodhpur Char Rasta	5.68	2.63	6.11	4.32	5.48	1.91	4.49	1.36
Shivranajini	12.32	4.74	14.16	5.90	13.76	5.97	13.70	4.87
Jhansi ki Rani	8.06	3.08	12.71	4.77	5.40	1.94	6.08	2.78
Nehru Nagar	10.3	3.79	10.47	3.71	8.84	3.59	8.85	3.811

Table 2. Statistics results of dwell time data at various stops along unsegregated stretch

Directions	Naroda to Iskon				Iskon to Naroda			
	Loading area 1		Loading area 2		Loading area 1		Loading area 2	
Bus stop name	Average dwell time(s)	Std. Dev.	Average dwell time(s)	Std. Dev.	Average dwell time(s)	Std. Dev.	Average dwell time(s)	Std. Dev.
G.C.S. Hospital	6.39	2.89	–	–	7.6	4.02	–	–
Kalupur Ghee Bazaar	7.44	3.92	–	–	No bus stop	–	No bus stop	–
Kalupur railway station	20.44	10.61	–	–	16.58	8.01	–	–
Sarangpur Darwaja	8.37	2.63	11.02	5.88	7.63	2.45	5.37	2.24

Table 3. Failure rate at bus stops

Segregated stretch				
Naroda to Iskon				
Bus stop name	Star Bazaar	Jodhpur Char Rasta	Shivranjini	Jhansi ki Rani
Failure rate	12.12%	18.92%	11.24%	8.70%
Iskon to Naroda				
Bus stop name	Star Bazaar	Jodhpur Char Rasta	Shivranjini	Jhansi ki Rani
Failure rate	15.15%	2.94%	29.78%	8.89%
Unsegregated stretch				
Naroda to Iskon				
Bus stop name	G.C.S. hospital	Kalupur ghee bazar	Kalupur railway station	Sarangpur Darwaja
Failure rate	Nil	Nil	Nil	Nil
Iskon to Naroda				
Bus stop name	G.C.S. hospital	Kalupur ghee bazar	Kalupur railway station	Sarangpur Darwaja
Failure rate	Nil	No Bus Stop	12%	2.13%

potential added amount of time spent waiting for a gap to pull back into traffic, known as re-entry delay.

Since all BRTS stops were on-line, there was no re-entry delay. Also since none of the BRT stops was at traffic signal and was away from influence of traffic signal, $g/c = 1$.

By using eq. (4), the loading area capacity of various stops was obtained. To estimate bus stop capacity, the loading area capacity was multiplied by the number of effective loading areas which is taken as 1.75 in case of two loading areas as arrival of buses was random[8]. Table 4 shows capacity of all BRTS stops.

Minimum capacity for the segregated stretch was at Shivranjini bus stop from Naroda to Iskon, i.e. 243 buses/h, and for the unsegregated stretch, it was at Kalupur railway station stop from Naroda to Iskon direction, that is 101 buses per hour.

It can be clearly seen that the minimum capacity of the corridor is at Kalupur railway station stop from Naroda to Iskon direction (101 buses per hour). So we can say that this is the capacity for hybrid BRTS corridor.

Greenshield model was applied on segregated stretch of BRT system to compare it with the empirical model. For this purpose, 4 h video data was collected on a midway section of 60 m length between Nehru Nagar and Jhansi ki Rani bus stops during peak band. After extracting this data, the speed, volume and density of buses were obtained. Greenshield model was applied

using these parameters. The basic equation of Greenshield model is

$$V = a + bK, \quad (6)$$

where K is density in buses/km, V the space mean speed in km/h and a and b are constants. Figure 3 shows the graph obtained using Greenshield model.

Table 4. Capacity values of BRTS stops

Stop name	Capacity (buses/h)	
	Naroda to Iskon	Iskon to Naroda
Segregated stretch		
Star Bazzar	336.65	340.59
Jodhpur Char Rasta	380.78	399.70
Shivranjini	243.14	270.62
Jhansi ki Rani	285.17	381.36
Nehru Nagar	298.78	321.72
Unsegregated stretch		
GCS hospital	251.39	212.38
Kalupur Ghee Bazar	215.62	No bus stop
Kalupur Railway Station	101.15	175.04
Sarangpur Darwaja	201.38	297.60

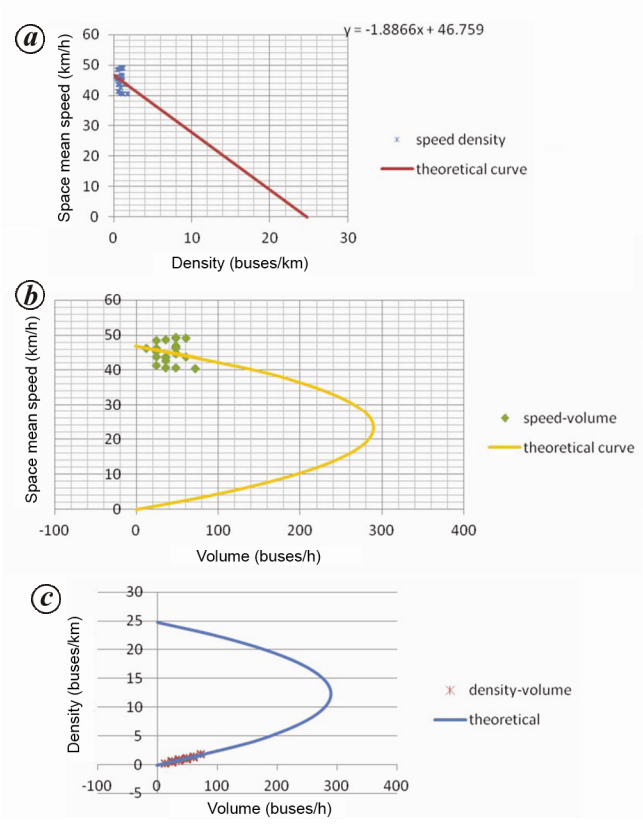

Figure 3. Interrelation graphs between speed, flow and density. ***a***, Speed–density; ***b***, Speed–volume; ***c***, Density–volume.

Capacity of segregated corridor using Greenshield model comes out to be 290 buses/h. This value is much greater than the capacity value obtained from the empirical model, i.e. 243 buses/h at Shivranjini BRTS stop.

After obtaining results from detailed analysis, it was observed that the Greenshield model overestimates the capacity of the BRTS. It estimated the capacity of segregated stretch of BRT as 290 buses/h, which was far more than 243 buses/h as obtained using empirical model. It was also observed that the data obtained at mid-block section of BRT system was concentrated near free-flow speed of BRT system with density values nearly 1 bus/km.

This limitation is of great concern as it is practically impossible to obtain wide range of data at a particular BRT section. Such data range is too small to extra-polate and it questions the applicability of Greenshield model or any other model (those used to estimate capacity of normal highway roads) to BRT system. Also the real impedence to bus traffic in BRT system is at BRT stop rather than at midway section.

Lastly, if we work on a mid-block section and try to find out the capacity, we would be unaware of the condition at BRTS stop, i.e. whether the failure rate is within limits so that there are no operation problems. Reduction in bus travel speeds, additional delays and decrease in bus scheduled reliability due to increased failure rate are some of the problems which cannot be taken care of, if we try to find out capacity by working on a mid-way section. So we can say the Greenshield model is not a good approach to estimate the capacity of a BRT corridor.

Literature review revealed that there was no research on capacity estimation of hybrid BRTS. Also most studies in India focused on performance evaluation of BRTS and studies involving capacity estimation were scarce. Hence, this study was carried out to estimate the capacity of hybrid BRT corridor.

The following conclusions are drawn from the study: (1) Capacity of hybrid BRT corridor was estimated as 101 buses per hour at 0% failure rate. Kalupur railway station stop was a critical bus stop which lies in unsegregated stretch (mixed traffic environment). This value was much less than the capacity of exclusive BRT stretch (243 buses/h at Shivranjini bus stop) and was roughly 42%. (2) The failure rate at most bus stops in unsegregated stretch including critical bus stop was nil. Buses experienced large delays due to mixed traffic causing increase in headway between them. As a result, the capacity values came out much lower than those of the exclusive BRT stretch. (3) The capacity value of the exclusive BRT stretch alone was appreciable. It was 243 buses per hour at a failure rate of 11%, i.e. nearly 4 buses per minute. Such a high value with dwell time value of 12.32 sec at critical bus stop (Shivranjini bus stop) could be possible due to the presence of 2 loading areas, which significantly increase the capacity of corridor by a factor of 1.75.

This study also tried to estimate the capacity of exclusive BRT (segregated stretch) stretch at midway section using Greenshield model, as no such study was done earlier. Capacity estimated from Greenshield model for a segregated stretch came out to be 290 buses per hour whereas that from empirical model was 243 buses per hour at Shivranjini BRT stop. The Greenshield model overestimated the capacity of segregated BRT stretch by 19.34%. It is impossible to collect wide data range at a particular mid-block section of a BRT system because of the movement of buses at constant density. So, with such a small data range, applicability of Greenshield model or any other model (that is applicable to normal highway traffic) to exclusive BRTS is questionable. Moreover major impedance to bus movement in BRTS is at bus stops. By considering all the aforesaid reasons it can be concluded that the Greenshield model is not a good approach to estimate the capacity of a BRTS.

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